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Letter to the Editor

Collision and gravitational reaccumulation: Possible formation mechanism of the asteroid Itokawa

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ABSTRACT

Aims. We investigate the possibility that the observed sea-otter shape of the asteroid Itokawa, associated with the presence of big boulders on its surface, originates from the reaccumulation process that may have formed this asteroid, assuming that it consists of reaccumulated fragments from a catastrophically disrupted parent body.

Methods. We computed the gravitational phase of an asteroid disruption, during which fragments can reaccumulate and form aggregates, using a version of the *N*-body code pkdgrav that includes a model of rigid aggregates. This new model allows the formation of non-idealized rubble piles as a result of reaccumulation that are made up of irregular, competent pieces. Shape and spin information of reaccumulated bodies are thus preserved by allowing fragments to stick on contact (and optionally bounce or cause further fragmentation, depending on user-selectable parameters), instead of merging into growing spheres.

Results. We find that the reaccumulation process of an asteroid disruption can produce aggregates whose form is similar to that of Itokawa, and can lead to the deposit of big boulders on the surface, as observed on Itokawa.

Key words. gravitation – methods: numerical – minor planets, asteroids: general – minor planets, asteroids: individual: Itokawa

1. Introduction

In this paper, we investigate numerically the possible shapes and other properties of fragments produced by gravitational reaccumulation following an asteroid disruption by a collision with a smaller projectile. In particular, we look for the possibility that Itokawa's shape and its large surface boulders originate from this process.

In the early 2000s, Michel et al. (2001) simulated the catastrophic disruption of a large asteroid for the first time. The simulation also included the following phase during which generated fragments can interact gravitationally with each other. It was found that fragments larger than a few hundred meters usually reaccumulate as a result of their mutual attraction and form larger bodies consisting of gravitational aggregates. This was confirmed by later works (e.g., Michel et al. 2002, 2003, 2004) and by other authors (e.g., Durda et al. 2004, 2007). However, in all these studies reaccumulating fragments were merged into growing spheres for simplicity and computational efficiency, and also because the first aim was to compare the numerical outcomes with only the size and ejection velocity distributions of asteroid family members. Thus, fragment shapes and other physical properties could not be investigated by these approaches.

More recently, Richardson et al. (2009) introduced a rigid body approximation to model gravitational aggregates in the numerical parallel *N*-body code pkdgrav used to compute the gravitational reaccumulation phase in previous studies. Several prescriptions for variable material strength/cohesion are used in this model that allow non-idealized rubble piles made up of irregular, competent pieces to be constructed; the model also allows shape and spin information of reaccumulated bodies in simulations of catastrophic disruption to be preserved. Fragments are thus allowed to stick on contact (and optionally bounce or cause further fragmentation, depending on user-selectable parameters), instead of merging into growing spheres (see Richardson et al. 2009, for details).

One of the motivations for this improvement in simulations of catastrophic disruptions and reaccumulation came from the images obtained by the Japanese mission Hayabusa by JAXA that visited the small near-Earth asteroid (25143) Itokawa in 2005 and successfully returned a sample to Earth in June 2010. The images of Itokawa showed the first compelling evidence that asteroids as small as a few hundred meters may be gravitational aggregates (Fujiwara et al. 2006). In particular, they showed that Itokawa is an irregular asteroid, about 500 m long, with a boulder-strewn surface. The abundance of boulders is in contrast with the very few number of craters: it seems that there is a greater abundance of loose material on Itokawa's surface than the available volume in the identified craters. Moreover, the ejection speeds of fragments formed during a cratering impact are, in general, expected to be larger than the escape speed from Itokawa's surface. So, a mechanism other than material ejection resulting from crater formation must be invoked to explain the great abundance of boulders.

One mechanism that may explain the presence of boulders at the surface of Itokawa (and possibly other similar bodies) is the so-called Brazil-nut effect, which requires that Itokawa essentially be a granular aggregate originally composed of a mixture of large and small fragments deep in its interior. In such a case, low-energy impacts that a small asteroid of this kind undergoes over its history can shake it, and large pieces initially located deep inside can move to the surface little by little, as observed when one shakes a small bucket composed of a mixture of sand grains and larger pieces; eventually the larger pieces will move to the top, which is a well-known phenomenon in granular matter physics related to convection in Earth's gravity environment and size segregation (e.g., Knight et al. 1993). However, it is not clear that this mechanism can work efficiently in a low-gravity environment like the one on Itokawa; it has been found experimentally that convection is much reduced in micro-gravity (Murdoch et al. 2013).

Another possible way to explain the presence of boulders is the reaccumulation process that may be at the origin of Itokawa itself. Indeed, if Itokawa is a rubble pile that was formed by gravitational reaccumulation following a large asteroid disruption, then it may be that reaccumulation works to form an aggregate composed of large reaccumulated blocks covered by smaller boulders (still large compared to the typical size of other surface material) that reaccumulated later on. Our ability to simulate a catastrophic disruption and the resulting reaccumulation by preserving shape and spin information allows us to better understand the reaccumulation process and how the material ends up in/on the reaccumulated bodies.

In Sect. 2, we recall the method used to simulate the gravitational phase of a collision that is described fully in Richardson et al. (2009). In Sect. 3, we apply this method to investigate a few asteroid disruption scenarios and determine whether we find results that are consistent with the reaccumulation outcome indicated above for Itokawa. Section 4 presents conclusions and perspectives. We note that because of the long computer time needed to perform such simulations, our intent here is not to perform an exhaustive investigation of the parameter space, but rather to present the most intriguing outcomes that we found in our first attempts that may then pave the way to realistic simulations of cases like Itokawa. More detailed investigations regarding specific cases or generalizations will be the subject of future studies, thanks to the continuing increases in computer power.

2. Numerical method

Simulations of asteroid disruption by a collision involve two phases: (i) the fragmentation phase that leads to the production of fragments as a result of crack propagation due to the impact; and (ii) the gravitational phase during which the fragments produced by fragmentation are ejected, feel their mutual attraction, and can eventually reaccumulate if this attraction is strong enough. The first phase is usually computed by using hydrodynamical codes in which an appropriate model of fragmentation must be introduced. Computed outcomes of this phase are then fed into an *N*-body code that simulates the gravitational phase of the collision. This method has been used in the original studies of collisions and reaccumulations by Michel et al. (2001) and in later studies. Here, we will not describe the numerical method used to simulate the fragmentation phase as this is not the topic of this paper, and we refer the interested readers to Benz & Asphaug (1994, 1999), Wünnemann et al. (2006), and Jutzi et al. (2008, 2009) for a description of some of the fragmentation models for non-porous or porous materials.

When the fragmentation of an asteroid as large as a kilometer or more is over, the number of fragments can be very large, especially if simulations of this phase have been performed with a high resolution so that fragments as small as a few tens of meters (those for which gravity can start playing a role) can be tracked. Typically, the number of such fragments can range between a few hundred thousands to millions, depending on the size of the original body. Therefore, to follow the gravitational evolution of such a large number of particles and compute their reaccumulation (including collision detection), an efficient *N*-body code is required. We use `pkdgrav`, a numerical gravity solver, first developed for cosmological modeling at the University of Washington (Stadel 2001). The code was adapted to treat hard-sphere collisions for planetesimal modeling (Richardson et al. 2000) and later for granular material modeling (Richardson et al. 2011). The main technical features of the code include a hierarchical tree algorithm for reducing the computational cost of interparticle force calculations and a complete parallel implementation for balancing work across an arbitrary number of processors.

Many aspects of the code, including the ability to model semi-rigid bodies (bonded aggregates), are, as far as we know, unique to `pkdgrav`. We refer to Richardson et al. (2009) for details regarding the implementation of bonded aggregates modeling in the code. What needs to be recalled here is that these aggregates can already exist at the start of a simulation, or can form gradually during a simulation if particle sticking is enabled, such as during reaccumulation. In the code, each aggregate is treated as a pseudo-particle with center-of-mass position and velocity computed from its constituent particles (which are otherwise treated as independent bodies). There are three supported collision outcomes for bonded aggregates: sticking on contact (to grow the aggregate); bouncing (computed for these generally non-central impacts using the method of generalized coefficients; e.g., Richardson 1995; Richardson et al. 2009); and fragmentation (wherein the particles involved become detached from their respective aggregates and proceed to bounce as rigid spheres, possibly releasing more particles). Currently the user can specify which of these outcomes are allowed, and the circumstances under which each is invoked (generally given as an impact speed threshold relative to the surface gravitational escape speed). Angular momentum is conserved in each case, while energy may be dissipated depending on the adopted coefficient of restitution.

The fragmentation outcome of an aggregate is a simple model of fracture formation at (and propagation from) the point of impact. Some simple strength models have also been implemented in an ongoing effort to mimic the stress response of real materials to rotation and tidal forces (see Holsapple 2007). Here, bonded aggregates are given a size-dependent strength ($S \propto R^{\alpha}$, where R is the aggregate effective radius, i.e., the radius of the equivalent-volume sphere) in the normal (tensile) or tangential (shear) directions, or both. The aggregate experiences no strain as the stress increases: it remains perfectly rigid until the strength is exceeded. The stress can arise from gravitational tidal effects as a result of close encounters with other bodies in the system, fast rotation, or both, and includes the effect of self-compression since all interparticle forces are computed explicitly, even those arising between particles within an aggregate. Particles experiencing excessive stress are liberated from the aggregate and become free particles in the system. Free particles that stick to an aggregate (if that outcome is allowed) immediately inherit the full strength of the aggregate.

In the following, we apply this model to the reaccumulation of fragments using a few outcomes of simulations of large asteroid disruptions with a 3D SPH hydrocode (Benz & Asphaug 1994) used in the past to study asteroid family formation (Michel et al. 2001, 2003).

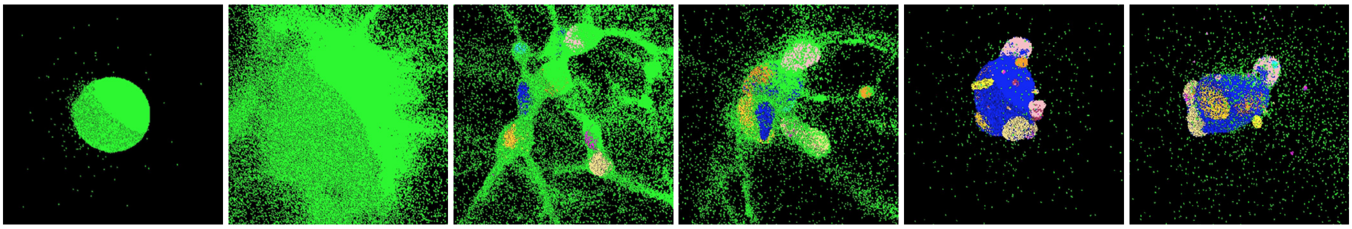

Fig. 1. Snapshots of the reaccumulation process following the disruption of a 25 km diameter asteroid. *From left to right*: first instant at the end of the fragmentation phase when all fragments (green dots) are about 200 m in diameter; the ejection of those fragments a few seconds later; the first reaccumulations that occur because of the slow relative speed between some fragments, showing the formation of a few aggregates represented by different colors; the formation of the largest fragment of this disruption by reaccumulation of several aggregates into a single body; and the final largest fragment shown at two different instants: the boulders on its surface and its overall shape are reminiscent of Itokawa.

3. Application: Itokawa-like fragments

In this section, we present an application of the numerical modeling of bonded aggregates in the context of asteroid disruption and reaccumulation. This application and its outcome open the possibility that some observed asteroid properties result from this process.

Here we investigate the reaccumulation process following the disruption of a 25 km diameter parent body made of basalt, as a result of the impact of a 1.21 km diameter projectile at 5 km s^{-1}, which corresponds to a specific impact energy of 1.13×10^8 erg/g. Typically, the fragmentation phase of this kind of disruption leads to the complete shattering of the targets down to the minimum particle size fixed by the resolution limit of the SPH simulations (see, e.g., Michel et al. 2001, 2002, 2003, 2004). The number of fragments at the end of the fragmentation phase in this particular run is 212 151, and their diameter is about 200 m each. As done in previous studies, their masses, radii, 3D positions, and velocities are then fed into the *N*-body code `pkdgrav` to compute the subsequent gravitational and reaccumulation phase over the first three days following the fragmentation. We note that the CPU time required to perform a parallel computation of this evolution over a few simulated days is a few months, using tens of processors.

In the nominal simulation with `pkdgrav` presented here, the integration step size is 5 s. We use a coefficient of restitutions (both normal and tangential) of 0.8. This value for the normal component is similar to the one measured for granite spheres by Durda et al. (2011) and for the satellite Hayabusa that bounced of the surface of the asteroid Itokawa (Yano et al. 2006).

We applied a size-dependent tensile and shear strength parameter of the form $S = C \times R^{-0.5}$ for the aggregate, where R is the aggregate effective radius, and C is a constant giving the strength of a centimeter-size particle. We consider here a value for C similar to the one measured by Housen & Holsapple (1999) for Georgia Keystone granite specimens, that is $C = 2.25 \times 10^8$ dynes/cm^2. The size-dependent strength accounts for the fact that larger bodies are weaker than smaller ones, because in nature they have a greater likelihood of having large cracks inside (e.g., Housen & Holsapple 1999). Thus, the strength of our aggregates does not only account for the self-gravity resulting from the different particle masses composing them, but also for some cohesion.

Figure 1 shows snapshots of the reaccumulation of particles that will eventually compose the largest remnant of this simulation. Its final mass corresponds to a few tens of percent of the mass of the parent body. The bulk of the body is composed of the particles that experienced the least amount of acceleration from the fragmentation phase (i.e., they reaccumulated immediately), but the rest consists mostly of smaller fragments that first reaccumulated elsewhere on their own and then fell back onto the largest remnant (this is made evident by the color scheme in the figure: aggregates that form independently retain a unique color, even if they subsequently bond with another aggregate).

The last instant of this simulation was already shown in Richardson et al. (2009), but it was not analyzed in great detail. As already remarked by the authors, it is interesting to compare this outcome with images of the asteroid Itokawa: similarities in overall structure and the presence of large surface components are striking. What is typically seen in simulations of disruption and reaccumulation is that once a large aggregate grows, smaller particles that are ejected at initially higher speeds but that are close enough to this forming aggregate can start feeling the gravitational influence of its growing mass and eventually slow down and reaccumulate onto it. In this model the sticking criterion was set to 10% of the relative escape speed, so most clumps and single particles bounce (with dissipation) for a while on the surface before sticking. We conjecture that this mechanism is a very plausible explanation for the large abundance of big blocks on Itokawa, as we already discussed in the introduction. However, we need to point out that the largest remnant that takes this shape and structure in this simulation (about 10 km in radius) is much larger than the 320-m diameter Itokawa. But we believe that the same kind of process can apply for much smaller aggregates in this simulation if we could achieve the same resolution for them. It is also possible that we could scale down this result starting with a smaller parent body (e.g., 1 km instead of 25 km), so that one of the largest remnants is the size of Itokawa. However, performing an exhaustive study is not possible at this stage, given the long CPU time needed for each simulation with current computer power. Also, it must be emphasized that we are using a very simple prescription for complicated mechanical processes. However, it is striking that one of our first usages of this new reaccumulation model in `pkdgrav` resulted in the formation of an aggregate that is the same shape as the smallest asteroid ever visited by spacecraft, and even resulted in an abundance of reaccumulated boulders that can possibly explain one of its mysteries.

For the sake of completeness, we also analyzed the properties of the set of gravitational aggregates formed by this simulation, which can serve as a point of comparison to observations of asteroid families formed by a catastrophic disruption. Figure 2 shows the mass spectrum, as well as the ejection speeds and spin distributions of the gravitational aggregates formed in our simulation. We verify that the outcome in terms of the size and velocity distributions does not change from the outcome using simple prescriptions (e.g., Michel et al. 2001). Moreover, we can now access the spin properties of the fragments. As can be

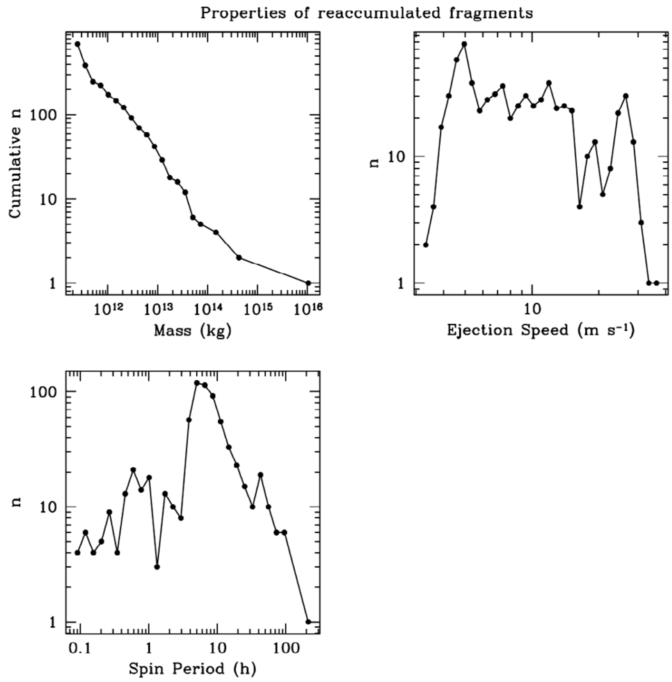

Fig. 2. Cumulative size distribution (*top left*), distribution of ejection speeds (*top right*), and distribution of spin periods (*bottom left*) of the full set of fragments and aggregates formed by the catastrophic disruption of a 25 km diameter body.

seen in Fig. 2, while fragments can take a wide range of spins, there is a peak at about 5−6 h, which corresponds to the average spin observed for main belt asteroids. Thus, reaccumulated fragments have realistic spins, which is a great advantage of using sticking rules and a rigid body model for simulating the reaccumulation process. This also suggests that, although the spin can be affected by small collisions and the YORP effect, some of the asteroids of second generation (generated by the disruption of a parent body) may have kept the memory of the original spin that was produced by the collision that gave birth to them; we note that initially, in the simulations of the fragmentation phase, the original parent body was not spinning.

4. Conclusions

Our first complete analysis of a simulation of the reaccumulation phase of a disruption using our new aggregate model suggests that shapes such as that of Itokawa, as well as the presence of large boulders on asteroid surfaces, can be due to the reaccumulation process that formed these bodies (for those that are fragments of larger ones). That Itokawa is possibly an aggregate (or rubble pile) is consistent with its low bulk density of 2 g/cm^3 (Fujiwara et al. 2006). The collisional lifetime of bodies of the size of Itokawa is smaller than one Gyr (Bottke et al. 2005), so such bodies are at least of second generation. In our modeling, the shapes of the aggregates formed by the reaccumulation process are parameter dependent. If we change the assumed strength of the aggregates or the bouncing coefficients, the final shape may be different. For instance, a preliminary simulation using a lower strength leads to a final largest aggregate that is more spherical. Because of the lower assumed strength, reaccumulating aggregates break more easily as a result of tidal and rotational forces, and therefore the object produced by this reaccumulation has difficulty keeping its irregular shape and instead becomes more and more rounded. Further studies are required to determine whether this type of outcome has some interesting implications, and to assess the actual sensitivity of the final shapes of reaccumulated objects to the parameters. It may be that we can provide some rough constraints on some of the mechanical properties of asteroids whose shapes are known, based on the parameters required to form them using our model, but this will need an extensive set of simulations that will require long runs with current computer power.

In conclusion:

1. We performed a full simulation of the reaccumulation process following an asteroid catastrophic disruption that accounts for the shapes of reaccumulating bodies.
2. Using material parameters for the aggregates that account for their size-dependent strength and bouncing coefficients similar to measured ones, we found that the shape of the asteroid Itokawa and the presence of large boulders on its surface can be formed by this process.
3. The size and ejection velocity distributions of the whole set of fragments are similar to those produced by previous numerical simulations of disruption that could not account for the fragments' shapes and are similar to those of real asteroid families.
4. Changing the material parameters of the aggregates can result in different shapes, more rounded, for example, when their strength is lower; but further studies are needed to assess the sensitivity of the parameters on the outcome and to understand which parameters lead to which observed shapes.

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References

Benz, W., & Asphaug, E. 1994, Icarus, 107, 98
Benz, W., & Asphaug, E. 1999, Icarus, 142, 5
Bottke, W. F., Durda, D. D., Nesvorný, D., et al. 2005, Icarus, 175, 111
Durda, D. D., Bottke, W. F., Enke, B. L., et al. 2004, Icarus, 170, 243
Durda, D. D., Bottke, W. F., Nesvorný, D., et al. 2007, Icarus, 186, 498
Durda, D. D., Movshovitz, N., Richardson, D. C., et al. 2011, Icarus, 211, 849
Fujiwara, A., Kawaguchi, J., Yeomans, D. K., et al. 2006, Science, 312, 1330
Holsapple, K. A. 2007, Icarus, 187, 500
Housen, K. R., & Holsapple, K. A. 1999, Icarus, 142, 21
Jutzi, M., Benz, W., & Michel, P. 2008, Icarus, 198, 242
Jutzi, M., Michel, P., Hiraoka, K., Nakamura, A. M., & Benz, W. 2009, Icarus, 201, 802
Knight, J. B., Jaeger, H. M., & Nagel, S. R. 1993, Phys. Rev. Lett., 70, 3728
Michel, P., Benz, W., Tanga, P., & Richardson, D. C. 2001, Science, 294, 1696
Michel, P., Benz, W., Tanga, P., & Richardson, D. C. 2002, Icarus, 160, 10
Michel, P., Benz, W., & Richardson, D. C. 2003, Nature, 421, 608
Michel, P., Benz, W., & Richardson, D. C. 2004, Icarus, 168, 420
Murdoch, N., Rozitis, B., Nordstrom, K., et al. 2013, Phys. Rev. Lett., 110, 018307
Richardson, D. C. 1995, Icarus, 115, 320
Richardson, D. C., Quinn, T., Stadel, J., & Lake, G. 2000, Icarus, 143, 45
Richardson, D. C., Michel, P., Walsh, K. J., & Flynn, K. W. 2009, Planet. Space Sci., 57, 183
Richardson, D. C., Walsh, K. J., Murdoch, N., & Michel, P. 2011, Icarus, 212, 427
Stadel, J. G. 2001, Ph.D. Thesis, University of Washington
Wünnemann, K., Collins, G. S., & Melosh, H. J. 2006, Icarus, 180, 514
Yano, H., Kubota, T., Miyamoto, H., et al. 2006, Science, 312, 1350